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A new geodynamic interpretation for the South Portuguese Zone (SW Iberia) and the Iberian Pyrite Belt genesis

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[1] The South Portuguese Zone (SPZ) constitutes the southernmost segment of the Variscan Iberian Massif. It is bounded to the north by the Beja-Acebuches Ophiolitic Complex and related accretionary wedge. To the south lie the Iberian Pyrite Belt (IPB) and flysch deposits forming the southern extent of the zone. Structural analysis within the Spanish side of the SPZ supports continuous south propagating deformation, evolving from early synmetamorphic thrusting in the internal zone to thin-skinned tectonics in the southern external domain. The accretion of the SPZ to the Ossa Morena Zone is also witnessed by the presence of various mélanges, observed throughout the investigated area. Part of the mélanges observed in the IPB are related to the volcanics and mineralizations setting. A key point to understand the IPB mineralizations genesis is to constrain the volcanogenic model. One underestimated feature is the large amount of submarine calc-alkaline ignimbritic facies, implying the presence of caldera structures within the province. Such correlation between caldera environment and ore deposits strongly suggests that the IPB developed in a continental arc. Our geodynamic model proposes an early north directed subduction associated with the obduction of the oceanic crust toward the south. Southward, this episode is immediately followed by the development of the accretionary prism, while farther south, a second subduction zone responsible for the arc setting of the IPB initiates. Subsequent Visean continental collision is associated with the deposit of the south propagating flysch and the present geometry of the SPZ. *INDEX TERMS:* 5480 Planetology: Solid Surface Planets: Volcanism (8450); 5475 Planetology: Solid Surface Planets: Tectonics (8149); *KEYWORDS:* Variscan belt, tectonics, volcanism, mélange, VMS, pyrite. **Citation:** Onézime, J., J. Charvet, M. Faure, J.-L. Bourdier, and A. Chauvet, A new geodynamic interpretation for the South Portuguese Zone (SW Iberia) and the Iberian Pyrite Belt genesis, *Tectonics*, *22*(4), 1027, doi:10.1029/2002TC001387, 2003.

1. Introduction

[2] The Iberian Massif represents one of the most extensive segments of the Variscan Belt of western Europe so that all the domains composing the whole belt are classically described herein. However, doubts remain on the real location of the sutures within the massif and their continuity along the Ibero-Armorican arc with other known sutures is still questioned. This paper deals with the South Portuguese Zone (SPZ), southern branch of the Iberian Massif, lying to the south of the Beja-Acebuches Ophiolitic Complex, the Iberian Massif southern suture commonly correlated to the closure of the Variscan Rheic Ocean (Figures 1 and 2). The central component of the South Portuguese Zone corresponds to the Iberian Pyrite Belt (IPB, Figure 2), one of the world most important metallogenic provinces for volcanogenic massive sulfide (VMS) deposits, remarkable for the numerous giant ore bodies (>100 Mt) such as Rio Tinto in Spain or Neves Corvo in Portugal (Figure 2).

[3] In spite of a large amount of work, especially during these last two decades, the geodynamic environment associated with the formation of the IPB is still debated [*Giese et al.*, 1994a; *Mitjavila et al.*, 1997; *Monteiro and Carvalho*, 1987; *Munha*, 1983; *Quesada et al.*, 1994; *Schütz et al.*, 1987; *Silva et al.*, 1990; *Soler*, 1980; *Thiéblemont et al.*, 1994, 1998]. Furthermore, models of ancient or present VMS mineralizations in arc, back-arc or mid-oceanic ridge environments do not explain the size and distribution of those observed in the IPB [e.g., *Fouquet et al.*, 1996, 1993; *Ohmoto and Skinner*, 1983]. Likewise some of the combined volcanologic and metallogenic models already proposed seem unlikely to explain the formation of observed explosive volcanic facies and to generate giant ore deposits. We want to oppose here a model of explosive submarine volcanism and caldera environment, against a nowadays commonly proposed intrusive model where all or part of the volcanism is considered as successive shallow intrusions [*Boulter*, 1993a, 1993b, 1996; *Soriano and Marti*, 1999].

[4] The aim of this paper is to present new data to constrain the geodynamic evolution of the South Portuguese Zone with special consideration on the obduction of the oceanic units and the setting of the Iberian Pyrite Belt. We thus propose a new interpretation based on (1) a global structural framework covering the Iberian Pyrite Belt and its northern edge, Pulo do Lobo Antiform and Beja-Acebuches Ophiolitic Complex, (2) a facies analysis of mélanges throughout the South Portuguese Zone, and (3) a reappraisal of volcaniclastic deposits. On the basis of our observations in the Spanish side of the South Portuguese Zone, we believe that the southern edge of the Iberian Massif results from a complex tectonic history involving two north directed oceanic subduction. The first subduction is associated with the obduction toward the south of the oceanic crust

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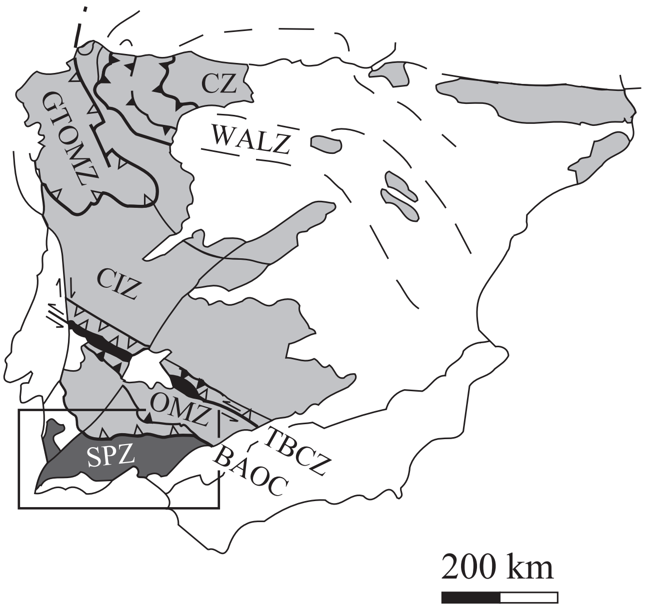

Figure 1. Iberian Variscan lithostratigraphic units [after *Ribeiro and Sanderson*, 1996]: CZ, Cantabrian Zone; WALZ, West Asturian-Leonese Zone; GTOMZ, Galicia Tras-os-Montes Zone; CIZ, Central Iberian Zone; TBCZ, Tomar-Badajoz-Cordoba Shear Zone; OMZ, Ossa Morena Zone; BAOC, Beja-Acebuches Ophiolitic Complex; SPZ, South Portuguese Zone.

along the northern edge of the South Portuguese Zone, the second being responsible for the IPB setting in a continental arc environment.

2. South Portuguese Zone: Place in the Variscan Orogeny and Main Lithostructural Features

[5] The Variscan Belt of western Europe is classically divided into three main domains: the central Armorican-Barrandian, the southern Moldanubian and the northern Saxo-Thuringian, and Rheno-Hercynian domains. These segments are separated by two lines of sutures running along the Variscan Belt from Eastern Europe to the Iberian Massif in western Europe. The Iberian Massif, covering the whole western side of the Iberian Meseta, represents the southwestern most segment of the West European Paleozoic belt. It is classically divided into six distinct tectonostratigraphic units (Figure 1). The northern Cantabrian, West Asturian-Leonese, and Galicia-Tras-os-Montes zones are related to the southern segment of the belt, the Central Iberian and Ossa-Morena zones are associated with the internal segment. Besides the South Portuguese Zone is commonly correlated with the northern domain of the belt [*Julivert et al.*, 1974; *Ribeiro et al.*, 1980, 1990; *Quesada*, 1991; *Ribeiro and Sanderson*, 1996]. However, the affinity of the South Portuguese Zone remains uncertain and pre-

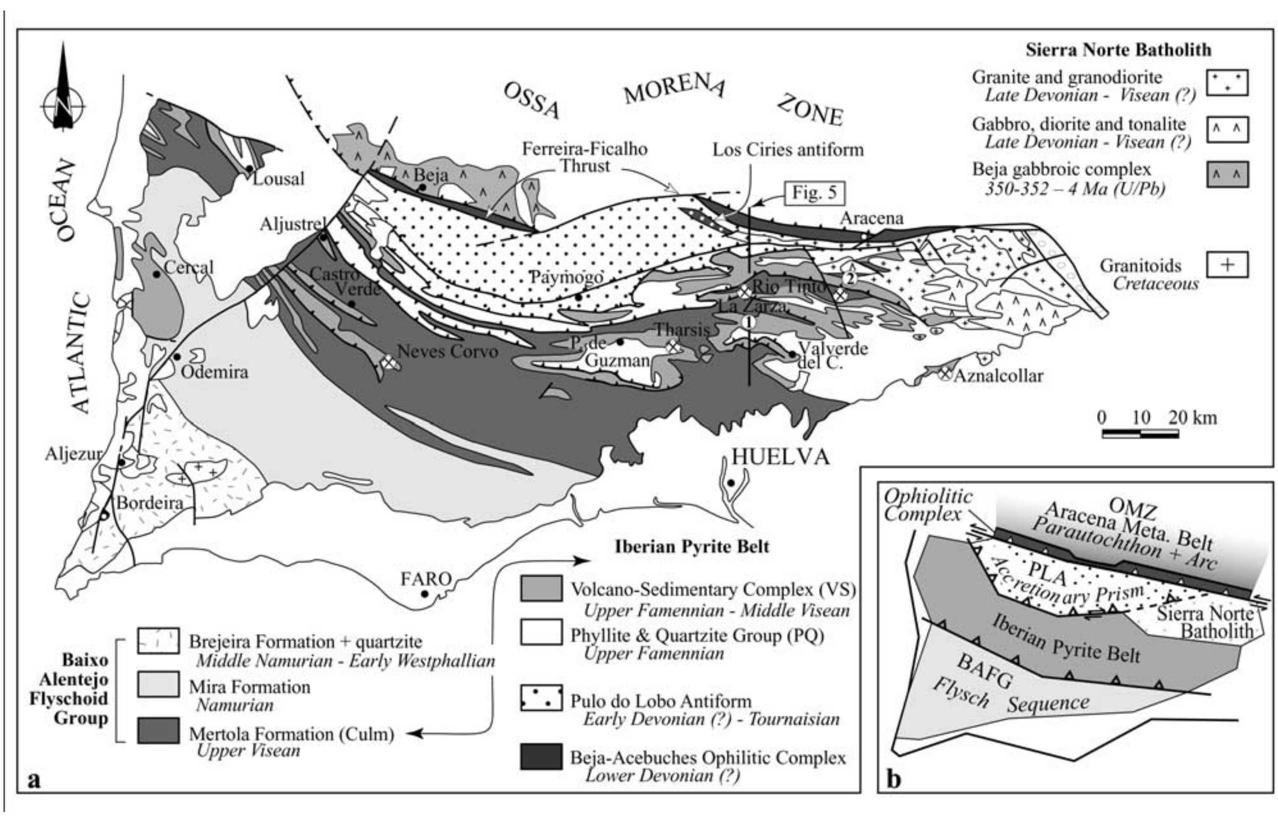

Figure 2. (a) Geological map of the South Portuguese Zone [after *Oliveira*, 1990]; (b) tectonic map of the South Portuguese Zone. The numbers 1 and 2 correspond to the locations of stratigraphic columns presented in Figure 8.

Devonian paleomagnetic data are lacking to clarify this point (the basement of the oldest unit of the Iberian Pyrite Belt, the Devonian Phyllites, and Quartzites Group, remaining unexposed).

[6] Within or at the border of these zones, several witnesses of obducted oceanic crust are observed within the Iberian Massif. To the north, within the Galicia-Tras-os-Montes Zone, mafic/ultramafic rocks are associated with major nappes rooted northward within the Ibero-Armorican Arc and thus related to the Eo-Variscan suture of the French Hercynian Belt [e.g., *Dias and Ribeiro*, 1995; *Burg et al.*, 1987]. Within the Iberian Massif this suture may be either linked to the Badajoz-Cordoba Shear Zone or northward to subunits transitions within the Central Iberian Zone (Figure 1) [*Ballèvre et al.*, 1992; *Hammann and Henry*, 1978; *Matte*, 1986; *Robardet et al.*, 1990]. The second occurrence of oceanic related rocks lies within the southern part of the Iberian Massif. It is associated to the Beja-Acebuches Ophiolitic Complex (Figure 2) [*Bard and Moine*, 1979; *Munha et al.*, 1986; *Quesada et al.*, 1994]. This other Variscan suture constitutes the boundary between two tectonostratigraphic units: to the north, the Ossa Morena Zone and to the south, the South Portuguese Zone. This suture is usually correlated to the Lizard Ophiolite (South Cornwall [*Eden and Andrews*, 1990; *Ribeiro et al.*, 1990; *Dias and Ribeiro*, 1995]).

[7] The Beja-Acebuches Ophiolitic Complex excluded, the South Portuguese Zone is composed in the sense of four Devonian-Carboniferous components, from north to south, the Pulo do Lobo Antiform, the Iberian Pyrite Belt, the Baixo Alentejo Flysch Group, and the South Portuguese Domain (Figure 2) [*Oliveira*, 1990]. Our work, mainly based on fieldwork completed within the Spanish part, will focus on the northern part of the South Portuguese Zone, Beja-Acebuches Ophiolitic Complex included. Sections 2.1–2.4 summarize descriptions of both lithologies and structures, respectively, observed in the above domains.

2.1. Beja-Acebuches Ophiolitic Complex

[8] The Beja-Acebuches Ophiolitic Complex is described as the south oceanic domain of the Aracena Metamorphic Belt, southern most subunit of the Ossa Morena Zone, while northern lying high-grade rocks belong to the continental domain [*Bard*, 1969; *Castro et al.*, 1996b]. Within its Spanish side, the oceanic domain is mostly made up of amphibolite facies metabasalts (the so-called Acebuches Amphibolite [*Bard and Moine*, 1979]), while in Portugal ultramafic rocks, mylonitic gabbro and sheeted dike complex have been documented [*Quesada et al.*, 1994]. This stratigraphic argument associated with normal/transitional mid-ocean ridge basalt (MORB) geochemical signature of the amphibolites allow to characterize these rocks as part of a relict oceanic crust lying in between the Ossa Morena Zone and the South Portuguese Zone [*Bard and Moine*, 1979; *Castro et al.*, 1996b; *Dupuy et al.*, 1979; *Munha et al.*, 1986; *Quesada et al.*, 1994]. The amphibolitic units, as well as the high-grade rocks of the Aracena Metamorphic Belt, are crosscut by intrusive mafic bodies such as the Beja gabbroic complex (Figure 2). This subduction-related magmatism characterized by boninitic signature [*Castro et al.*, 1996a], is also supported by calc-alkaline volcanism developed within the Portuguese side of the Ossa Morena Zone (the so-called Toca da Moura Volcanism [*Santos et al.*, 1990, 1987]).

[9] Recent U/Pb ages on zircon of the Beja complex are close to 350 Ma (350 and 352 ± 4 Ma [*Pin et al.*, 1999]), while $^{40}Ar/^{39}Ar$ ages are circa 340 Ma either in the gabbro or the surrounding amphibolites [*Dallmeyer et al.*, 1993; *Ruffet*, 1990]. The Ar/Ar age may be interpreted as a cooling age or more likely as reflecting the age of the late phase of deformation and coeval metamorphic event affecting the amphibolites.

2.2. Pulo do Lobo Antiform (PLA)

[10] The Pulo do Lobo Antiform lies south of the Beja-Acebuches Ophiolitic Complex, along the southern edge of the Fereira-Ficalho thrust (Figure 2). It is a Devonian in the sense of detrital unit composed of several formations which description, name and number given in the bibliography vary from the Spanish to the Portuguese areas [*Crespo-Blanc*, 1989; *Eden*, 1991; *Giese et al.*, 1994a; *Giese et al.*, 1988; *Oliveira*, 1990; *Oliveira et al.*, 1986]. However, on a general point of view the lowest units are mostly composed of phyllites, quartzites, and minor acidic dykes and evolve toward the top to a turbiditic sequence. The latter is made up by phyllite, siltstone, quartzite, tuffite, and graywacke, its composition shows a strong amount of volcanic fragments of acidic and mafic composition [*Giese et al.*, 1994a]. Within the core of the Los Ciries antiform (Figure 2), the Peramora Formation is considered as the bottom of the PLA succession. It consists in series of phyllites metamorphosed in the greenschists facies, enclosing amphibolitic, gabbroic and ultramafic blocks (see below) [*Eden*, 1991]. As a whole, the Pulo do Lobo Antiform, which composition evolves from pre/early orogenic units to synorogenic sequence, is interpreted as an accretionary prism developed during the north directed subduction of an oceanic domain under the Ossa Morena Zone [*Eden*, 1991; *Onézime et al.*, 1999; *Quesada et al.*, 1994].

[11] Ages of the Pulo do Lobo Antiform, based on palynologic data, remain poorly documented. However, within intermediate formations, palynomorphs yielded Givetian-Frasnian ages, while spores and acritarchs gave Late Devonian-Early Carboniferous ages toward the top of the sequence [*Eden*, 1991; *Giese et al.*, 1988; *Oliveira et al.*, 1986]. These ages indicate an early middle Devonian age for the basal formation of the accretionary wedge.

2.3. Iberian Pyrite Belt (IPB)

[12] This well-known metallogenic province can be described as a succession of three Devonian to Dinantian formations: the Phyllites and Quartzites Group (PQ), the Volcano-Sedimentary Complex, and the Culm (Figure 2) [e.g., *Schermerhorn*, 1971]. The Devonian in the sense of the Phyllites and Quartzites Group corresponds to a passive margin detritic sequence and constitutes the oldest unit observed to the south of the Pulo do Lobo Antiform. Its footwall remains cryptic; however, geophysical studies have

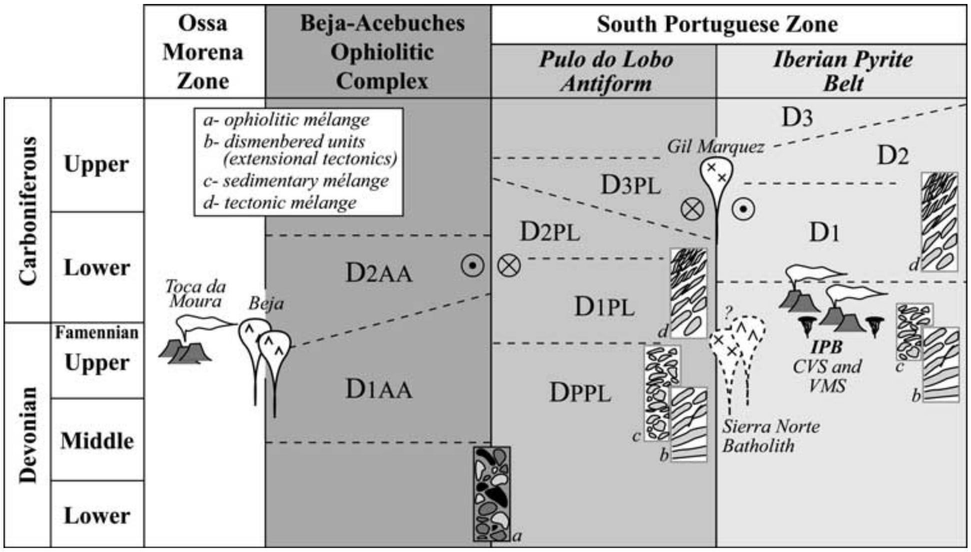

Figure 3. Tectonic evolution of the South Portuguese Zone. Summary of the main tectonic events recognized within the Beja-Acebuches Ophiolitic Complex and the northern domains of the South Portuguese Zone. The added cartoons show the position of the observed mélanges.

stressed a zone of low velocity evolving between 7 and 13 km depth from south to north, suggesting the presence of a major hinterland dipping crustal décollement [*Monteiro Santos et al.*, 1999; *Prodhel et al.*, 1975; *Ribeiro and Silva*, 1983].

[13] Sedimentological studies suggest the existence of catastrophic delta fan deposits toward the PQ hanging wall, at the Famennian transition with the overlying Volcano-Sedimentary Complex (VSC) [*Moreno et al.*, 1996]. This VSC is commonly described as a bimodal volcanic unit interfingered with siliceous/carbonaceous shales, volcanogenic facies and Mn-rich chert deposits [e.g., *Lécolle*, 1977; *Leistel et al.*, 1998; *Mitjavila et al.*, 1997; *Oliveira*, 1990; *Routhier et al.*, 1980; *Schermerhorn*, 1971; *Soler*, 1980; *Soriano and Marti*, 1999; *Van den Boogaard*, 1967]. The volcanogenic massive sulfide deposits of the Iberian Pyrite Belt are enclosed in the VSC and show variable relationships with their host rocks. Some of them are spatially closely associated with acidic volcanic formations (e.g., Rio Tinto) while other are disconnected and interlayered with shales (Tharsis [e.g., *Saez et al.*, 1996, 1999; *Strauss and Madel*, 1974; *Strauss et al.*, 1981; *Tornos et al.*, 1998]). The uppermost unit of the IPB, the Culm, corresponds to a Visean flyschoid sequence commonly associated with the Baixo Alentejo Flysch Group [*Oliveira*, 1983; *Oliveira et al.*, 1979]. However, in this study as in many others, we propose to consider the base of the Baixo Alentejo Flysch Group, the Culm formation, as part of the Iberian Pyrite Belt, both sequences being closely associated. The Culm is composed of three subunits: the basal shaly formation, a main turbiditic sequence and a limited sandstone formation [*Moreno*, 1993]. Large conglomeratic lenses are described within the Culm (several kilometers lateral extent), they enclosed polygenic elements though the volcanogenic components are important suggesting that the VSC is the main feeding source [*Schermerhorn*, 1971; *Oliveira*, 1988].

[14] The northeastern part of the IPB is intruded by the Sierra Norte batholith (gabbroic to granitic compositions). Some authors consider this magmatism as late Variscan, thus late compared to the IPB volcanism, while others estimate that both are genetically and temporally connected [*De la Rosa*, 1992; *Simancas*, 1983; *Schütz et al.*, 1987; *Soler*, 1980; *Stein et al.*, 1996; *Thiéblemont et al.*, 1994]. The lack of published radiochronologic constraints on the batholith does not allow us to solve this problem by comparing with the circa 350 Ma U/Pb ages obtained on felsic volcanics of the VSC [*Quesada*, 1999]. However, both U/Pb and Ar/Ar datations realized on the Gil Marquez pluton, syntectonic granodioritic apophyse developed on the western end of the Sierra Norte batholith, gave a Visean age (328 ± 2 and 330 ± 3 Ma, respectively [*Kramm et al.*, 1991; *Onézime*, 2001]). These data support a large gap between both magmatic events, or more precisely between IPB volcanism and the Gil Marquez pluton setting. It is indeed still hazardous to extend this to the whole batholith, which may reflect a rather long-lasting magmatism.

2.4. Structural Features Within the SPZ: An Overview

[15] Structural analysis of each component described above, reveals a polyphased tectonic history. Tectonic events show, in a south verging structural framework, an evolution from early tangential tectonics recorded within the internal unit evolving to a thin-skinned tectonics in the foreland domain. These features are partially (if not totally) overprinted by secondary strike-slip tectonics developed at different time during the accretion of the South Portuguese Zone to the Iberian parautochthon (Ossa Morena Zone). All the documented events are summarized here from the hinterland to the foreland units of the South Portuguese Zone and adjacent unit (Figure 3).

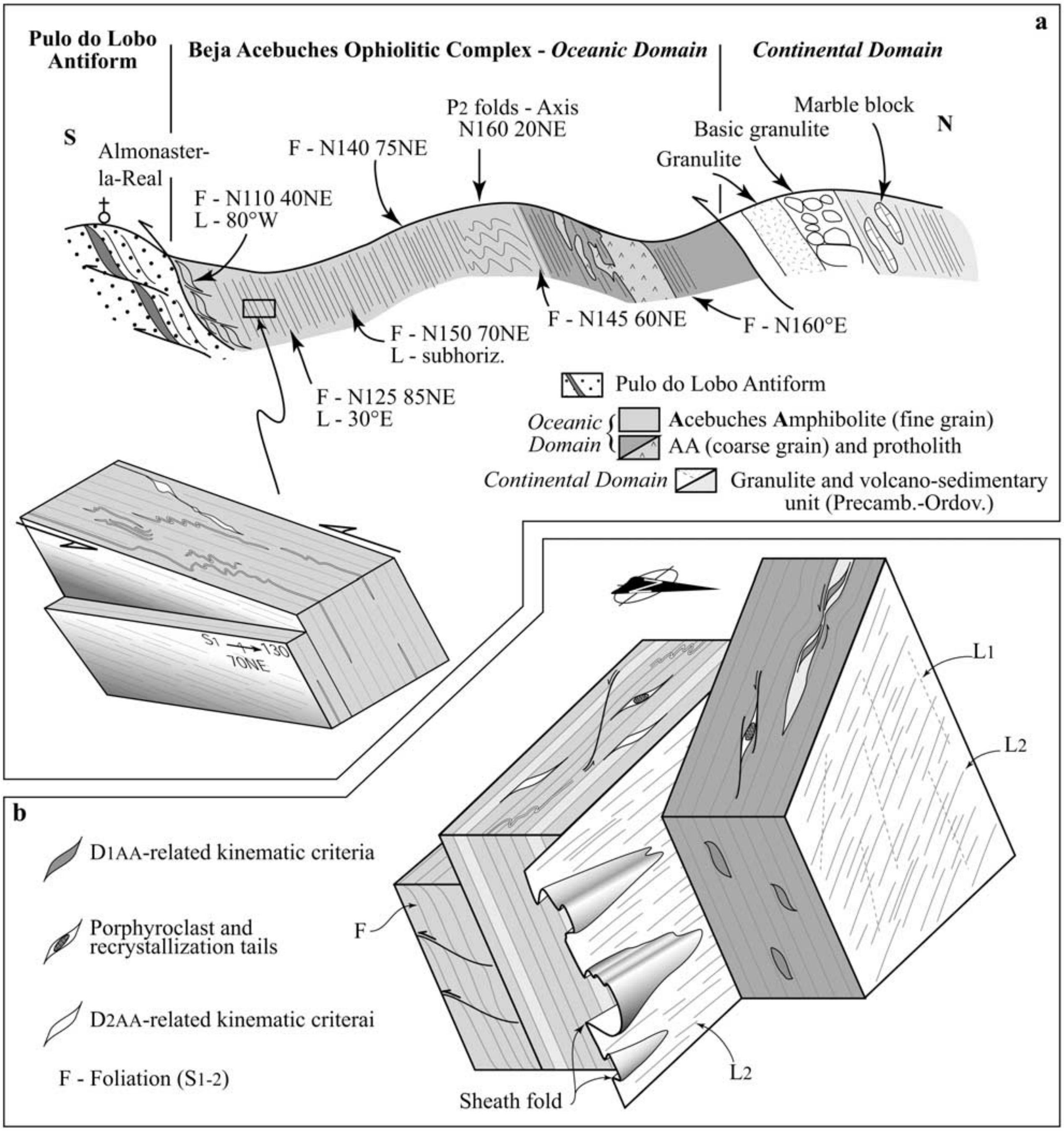

Figure 4. Structural features within the Beja-Acebuches Ophiolitic Complex. (a) Cross section and (b) synthesis of the observed kinematic criteria.

[16] Structural elements within the Beja-Acebuches Ophiolite Complex have been described in numerous works, and despite divergences, they all conclude a polyphase tectonic history [*Bard*, 1969; *Castro et al.*, 1996a; *Crespo-Blanc and Orozco*, 1988; *Fonseca and Ribeiro*, 1993; *Giese et al.*, 1994a; *Onézime*, 2001; *Onézime et al.*, 2002; *Quesada et al.*, 1994]. Our fieldwork in Spain points out the existence of two kinds of kinematic criteria both associated to two distinct lineations developed within the foliated/layered amphibolite (Figure 4). The first episode of deformation, correlated to the vertical down-dip lineation, characterizes a top-to-the-south kinematics. The second one, associated to a shallow dipping stretching lineation, describes a penetrative left-lateral wrenching event. Structural elements associated with the first episode remain poorly preserved and only observed in preserved primary

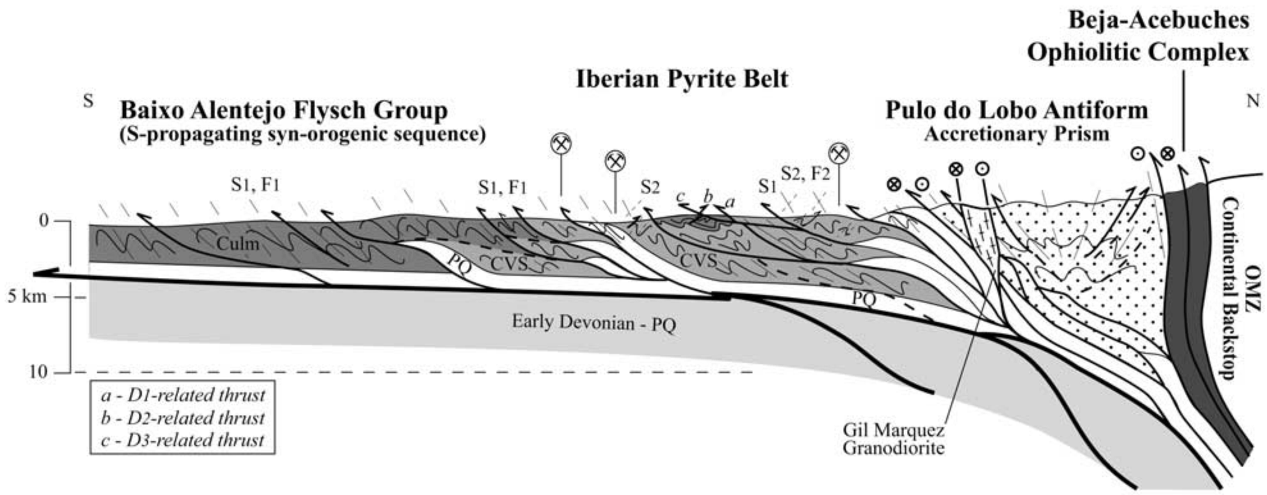

Figure 5. Cross section of the South Portuguese Zone.

amphibolitic facies unlike widespread secondary kinematic features [*Onézime*, 2001; *Onézime et al.*, 2002]. Indeed the latter developed with a coeval retrometamorphic event responsible for the retrogression of amphibolites within the greenschist facies [e.g., *Castro et al.*, 1996a; *Onézime et al.*, 2002; *Quesada et al.*, 1994].

[17] The Pulo do Lobo Antiform underwent a complex structural history [*Eden*, 1991; *Onézime et al.*, 2002; *Silva et al.*, 1990]. It experienced three episodes of folding, the oldest and youngest ones remaining weakly developed. The first episode (D_{PPL}, Figure 3) is characterized by intrafolial folds and can only be observed within the Peramora Formation. The second conspicuous folding event (D_{1PL}, Figure 3) shows folds with a south verging geometry in the southern part of the PLA, and north verging geometry in its northern part. Axial plane cleavage, shear bands and related top-to-the-south criteria within the southern area as well as top-to-the-north criteria within the northern area define a fan-like attitude of structural features within the Pulo do Lobo Antiform [*Onézime et al.*, 1999]. On a tectonic point of view such geometry supports the accretionary prism interpretation proposed for the Pulo do Lobo Antiform (Figure 5). The third and last folding event (D_{2PL}, Figure 3), associated with centimeter- or meter-scale upright folds, refold limbs of the second generation of folds. Furthermore, structures formed during two strike-slip episodes are preserved. The first one is developed along the Ferreira-Ficalho thrust (PLA northern limit, Figure 2). The associated sinistral kinematic indicators are similar to those observe within the Beja-Acebuches Ophiolitic Complex. On the opposite side, along the southern edge of the PLA, right-lateral wrenching can be documented. It is associated with the syntectonic Gil Marquez granodiorite intrusion at circa 330 Ma (Figure 2) [*Kramm et al.*, 1991; *Onézime*, 2001] and correponds to the last episode of deformation within the Pulo do Lobo Antiform [*Onézime et al.*, 2002].

[18] The structural analysis of the Iberian Pyrite Belt is now commonly described through a thin-skinned tectonics model [*Leca et al.*, 1983; *Onézime*, 2001; *Onézime et al.*, 2002; *Quesada*, 1998; *Ribeiro et al.*, 1980; *Ribeiro and Silva*, 1983; *Silva et al.*, 1990; *Soriano*, 1996]. This belt first underwent a south verging event (D_1, Figure 3) responsible for a thrust tectonics associated with passive south verging folding and a roughly E-W striking and north dipping axial plane cleavage (S_1, Figure 3). Secondary north verging folds are geometrically associated with the main thrusts (D_2, Figure 3). They deform S_1 and produce an E-W striking and south dipping S_2 axial plane. However, in the mean time, some D_2-related south verging folds can also be documented. Finally, the above mentioned features are crosscut by late out-of-sequence, top-to-the-south thrusts (D_3, Figure 3). All of these observations support a model of continuous south verging thin-skinned tectonics, associated with a basal crustal décollement, showing local back thrusting well documented in fold and thrust belt (Figure 5).

3. Mélanges in the Study Area

[19] Introduced by *Greenly* [1919], the term mélange is usually employed to define formations characterized by blocks of native or exotic material reworked into a fine-grained pelitic matrix. Several authors proposed classifications based on the nature of blocks and on the sedimentary, tectonic, diapiric or combinations of processes of formation [e.g., *Cowan*, 1985; *Raymond*, 1984]. Mélanges are not exclusive to a particular setting; nevertheless they are commonly associated and recognized in subduction-related environments. They are thus regarded in this study as witnesses of major tectonic instabilities located at convergent plate boundary environment and either related to contractional or extensional tectonics. Within the South Portuguese Zone mélange facies are ubiquitous from base to top and can be documented either in the Pulo do Lobo Antiform or the Iberian Pyrite Belt. There are three different types of mélange, based on composition and temporal

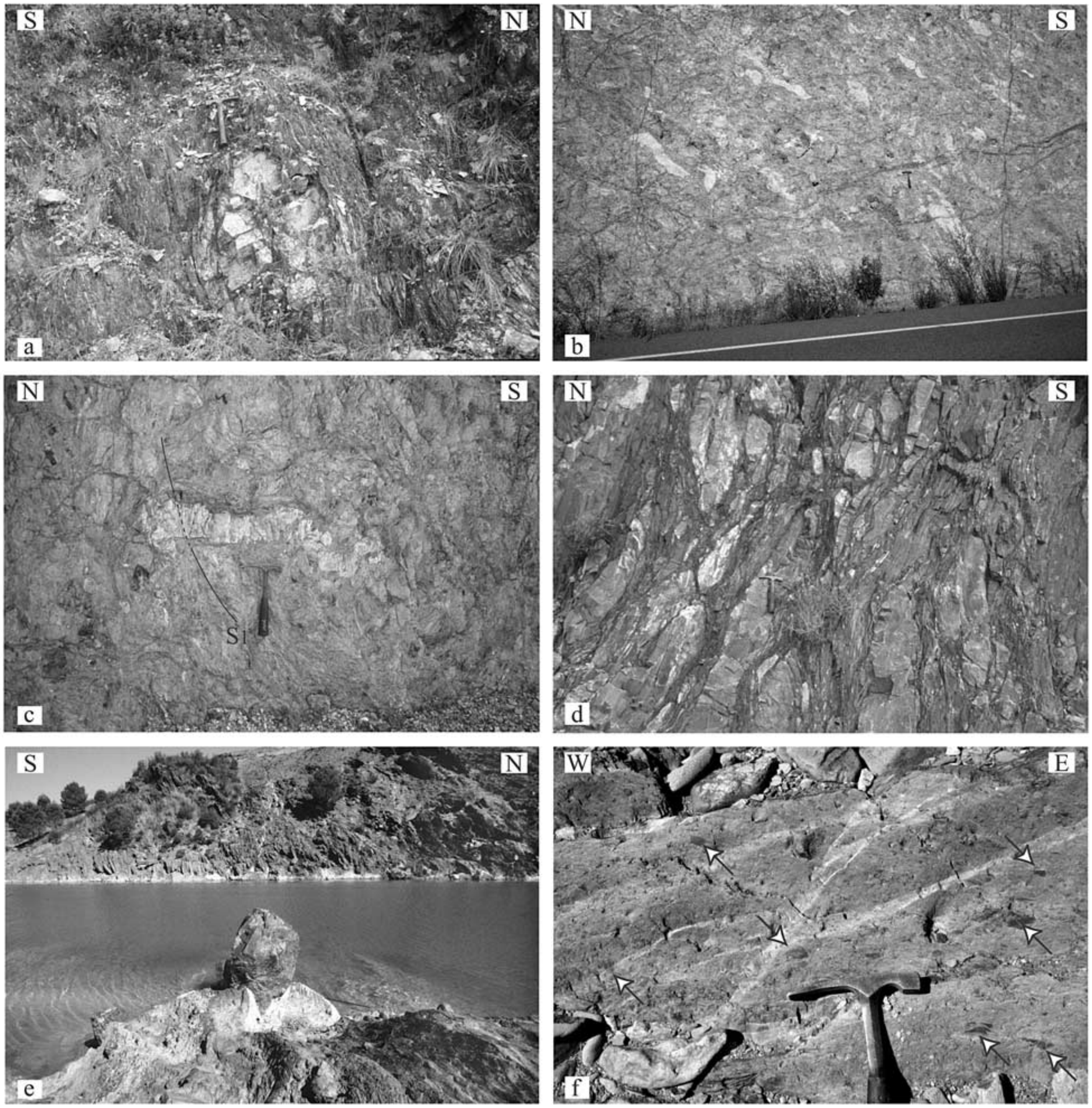

Figure 6. Mélanges throughout the Pulo do Lobo Antiform and the Iberian Pyrite Belt. (a) Block of amphibolite in the Peramora ophiolitic mélange (Los Ciries antiform); (b) general overview of the sedimentary mélange (north of the Aserrador river); (c) detail of a block within the Aserrador mélange, note the cleavage (S_1) crosscutting the quartzite block; (d) sheared quartzite in the Almonaster tectonic mélange (Almonaster la Real); (e) metric block of sandstone in the Phyllites and Quartzites formation along the Odiel river (Sotiel area, PQ formation); (f) pebbly mudstone facies enclosing this block.

relationship with deformational events, ranging in age from Early Devonian in the PLA to Visean in the IPB.

[20] The first kind remains peculiar and only observed within the Pulo do Lobo Antiform. First described by *Eden* [1991], this mélange (the so-called Peramora mélange) crops out at the base of the Pulo do Lobo formation in the core of the Los Ciries antiform (Figure 2). Blocks of amphibolite and gabbro occur, reworked in a fine-grained basic matrix metamorphosed in the greenschist facies (Figure 6a). *Eden* [1991] also described the presence of serpentinite blocks. Such composition of the mélange, enclosing most types of rocks associated with an ophiolitic sequence, characterizes an ophiolitic mélange. The formation of this mélange might be related to early intraoceanic tectonic

process active along transform faults, therefore before its addition (accretion) to the accretionary prism. Such a model has been proposed to explain the formation of similar ophiolitic mélange observed within the Mikabu greenstone belt (SW Japan [*Faure*, 1985; *Iwasaki*, 1979]). Its metamorphic paragenesis is characterized by the presence of garnet, signifying that this formation underwent higher P/T conditions than the overlying units of the PLA. This may suggest that the mélange has been first underplated at the bottom of the prism, underplating accommodated by duplex structures, and later exhumed during the collisional episode and the related deformation (thrusting and folding) of the accretionary prism.

[21] The second type of mélange observed in the PLA, is characterized by both white and grey quartzite blocks, ranging from meter to decimeter, reworked in a fine shaly matrix (Figure 6b). Blocks are here poorly transposed in the main cleavage, moreover some of them are clearly crosscut by S_1 (Figure 6c), arguing for an early incorporation of the exotic blocks into their matrix by debris flow process. This mélange can be compared to formations observed along the Pulo do Lobo Antiform-Beja-Acebuches Ophiolitic Complex boundary (the so-called Alajar mélange [*Eden*, 1991]). These are made up of dominant monogenic blocks of quartzite, with minor marble, chert and amphibolite/serpentinite elements, all reworked in a phyllitic matrix, thus showing the same patterns as the second type of mélange. These mélanges reflect a submarine sequence fed by continental margin deposits. Indeed the important amount of continental blocks supports the transport from the north (overriding plate, in the proposed model). Thus marble blocks described by *Eden* [1991] can either be compared to the Cambrian marble observed north, within the volcano-sedimentary sequence of the Aracena Metamorphic Belt (i.e., the arc) or to resedimented shelf deposit from a possible forearc basin. Two origins and processes can be proposed for the quartzite blocks. They can either result from submarine slides generated along the trench slope and collected within trench slope basins or debris flow produced in the off-scraping zone, above the imbricated thrusts system, at the edge of the accretionary prism. The origin of ophiolitic material within the mélange most likely corresponds to the obducted ophiolitic sequence, lying in between the southern edge of the arc and the accretionary prism.

[22] The third type of mélange is also developed at the contact of the Acebuches Amphibolite along its tectonic boundary with the Pulo do Lobo Antiform, the Ferreira-Ficalho thrust. Although quartzite blocks appear isolated in some outcrops along the thrust (see above), some formations appear mostly composed by tectonically disrupted quartzite beds (Figure 6d). Here then, the mélange appears to result from the shearing of quartzite layers, progressively dismembered and isolated as blocks in a shaly matrix. Such a mélange is also observed toward the south of the Pulo do Lobo Antiform. Here folded layers of graywackes are sheared apart, partially or completely disrupted leading to rootless fold hinges and isolated blocks.

[23] Within the Pulo do Lobo Antiform we are thus able to describe three kinds of mélange, emphasizing the complete evolution of the accretionary complex. The Peramora ophiolitic mélange reveals early intraoceanic processes developed before the building of the PLA, testifying for preprism mélange. The second kind of mélanges is associated with secondary trench-filling processes, active during the building of the accretionary prism (i.e., synprism) and reflecting in part the dismantling of the northern lying arc. This is supported by the composition of some of the PLA detrital units, showing important amount of volcanoclastic materials [*Giese et al.*, 1988, 1994b]. Gravity flow deposits developed within the accretionary prism are as well responsible for the formation of such kind of mélange. The third and last type of mélange results from local intense deformation of Pulo do Lobo Antiform units, thus highlighting the last step of the accretionary prism history. Shearing is here a powerful progressive process, responsible for the generation of tectonic mélange. Considering the prolonged and complex deformational history of the PLA (Figure 3), these mélanges could have been generated early or late with respect to the development of the accretionary wedge.

[24] South of the Pulo do Lobo Antiform, within the Iberian Pyrite Belt same kinds of mélanges can also be described (ophiolitic mélange excepted). Along the northern limb of the Puebla de Guzman antiform (Figure 2), toward the top of the Phyllites and Quartzites Group, in addition to the presence of bioclastic limestone lenses [e.g., *Van den Boogaard*, 1967], some pebbly mudstone facies can be recognized. They are made up by heterogeneous (different sizes) quartzite blocks, reworked in a shaly matrix (Figures 6e and 6f). Some pebbly mudstones are associated with conglomeratic facies and several meter thick and length quartzite layers. The discordant lower boundaries between these layers and underlying shales, conglomerates or pebbly mudstones, make us believe that this important quartzite formation can be interpreted as an olistolith. This interpretation is strengthened by the nature of surrounding formations briefly described above, supporting a gravity flow environment [*Moreno et al.*, 1996].

[25] Along major tectonic boundaries (main thrusts) where the Phyllites and Quartzites Group is thrust to the south over the Culm (Figure 2), PQ rocks show strong ductile deformation patterns. Inversely, the underlying Culm shales and graywackes are less deformed, with a preserved folded S0 (upright to slightly reversed folds). The PQ is there very similar to the PLA tectonic mélange (our third type) exposing many quartzite/sandstones beds sheared toward the south, progressively dismembered (boudinage) and isolated as blocks in a pelitic matrix.

[26] It appears then that the same evolution of mélanges, first described within the Pulo do Lobo Antiform, can also be observed in the IPB within its PQ unit. The presence of olistoliths and pebbly mudstones toward the top of the PQ implies tectonic instabilities at the PQ-VSC transition [*Moreno et al.*, 1996], responsible for the formation of sedimentary mélange, built up by either exotic (presence of limestone lenses) or native blocks. Extensional tectonics affecting the Phyllites and Quartzite Group must be also considered. These are related to VSC magmatism/volcanism

setting and subsequent evolving geodynamic environment from passive margin to active arc (see below).

[27] The presence of large conglomeratic lenses rich in volcanic elements within the Culm [*Oliveira*, 1983; *Schermerhorn*, 1971] (i.e., the Volcano-Sedimentary Complex is the main alimentation zone), suggests that sedimentary mélanges occur during the synorogenic Visean flysch development as well, while tectonic mélanges develop in the underlying Phyllites and Quartzites Group. The two coexisting mélange facies have already been described and considered as synchronously deposited [*Vollmer and Bosworth*, 1984]. Considering a foreland overthrust environment, sedimentary mélanges result from gravity flows in a foreland basin, while in the same time, shearing induces disruption of the formerly deposited sequence.

[28] In contrast with the Phyllites and Quartzites Group, the Volcano-Sedimentary Complex remains well preserved emphasizing contrasting rheological behavior between lavas of the VSC and quartzite/sandstones of the PQ. Besides the VSC did not undergo previous extensional tectonics. However, blocks can also be documented within the Volcano-Sedimentary Complex (mostly chert blocks), but they are mostly associated with true volcaniclastic deposits (ignimbrites, see below) or resedimented volcaniclastic facies. Most of the blocks are regarded here as lithic element reworked and assimilated by volcaniclastic flow during their setting.

4. Volcanism in the Iberian Pyrite Belt: A Preliminary Reappraisal

[29] Volcanism in the Iberian Pyrite Belt is usually described as bimodal in composition, submarine and effusive [e.g., *Mitjavila et al.*, 1997; *Thiéblemont et al.*, 1998]. Despite important amounts of volcaniclastic deposits, a complete intrusive model has been proposed to describe volcanic facies in the Iberian Pyrite Belt [*Boulter*, 1993a, 1993b, 1996]. Others considered a partial intrusive model, interpreting all the volcaniclastic facies as submarine autobrecciated lavas locally resedimented, leading to fine-grained deposits [*Soriano and Marti*, 1999]. Our fieldwork and facies analysis in thin section allow us to propose another volcanological interpretation for the VSC, involving a new interpretation for both volcaniclastic and ore deposits environment.

[30] First observations on the volcanic and volcaniclastic facies support a submarine emplacement of lavas or deposition of volaniclastic deposits. This is documented by pillow lava, the presence of granulation features in acidic lava interpreted by *Boulter* [1993b] as peperitic facies (Figure 7a). Massive or autobrecciated acidic and intermediate lava are consistent with extrusive emplacement (domes may be envisaged for dacite or rhyolite). On the other side, volcaniclastic deposits show widespread glass shards facies throughout the whole VSC, constituting significant parts of the stratigraphic section (Figure 8). Even if some of the in situ macroscopic analysis of such deposits supports the interpretation of pyroclastic deposits sometimes rich in lithic fragments (ignimbrites, Figures 7b, 7c, and 7d), in thin section a strong secondary overprint does not allow the distinction with resedimented depositional units (Figures 7e and 7f). Indeed all these facies are affected by the regional deformation but also show hydrothermal alteration characterized by intense sericitization and less important chloritization associated with devitrification. However, such deposits imply that large volumes of ignimbrite material were erupted in the province, deposited primarily by pyroclastic flow (ignimbrite) and then eventually partly or completely redeposited by secondary density currents. All depositional units are now observed in marine sequences, and there likely exist both primary submarine ignimbrite and resedimented ignimbritic material.

[31] The presence of these large volumes of ignimbrites in the province strongly suggests the formation of large caldera structures as anticipated on the interpretative Figure 9. This is in agreement with the existence of extrusive silicic facies, caldera structures being preferential sites for silicic dome emplacement. Close geometrical relationships between domes and ignimbrites allow us to conclude that they together identify former caldera sites. Given this anticipated link between silicic domes and calderas in the VSC and also given the fact that all observed silicic domes and ignimbrite-type depositional units are found in submarine environments, the calderas themselves must have been submarine, and so likely were the ignimbrites, considering that such flows/eruptions may take place up to 1000 m below sea level [e.g., *Cas*, 1992; *Large*, 1992].

[32] For a metallogenic perspective, such caldera environments in the South Portuguese Zone could explain the presence of exceptionally important and localized volcanogenic massive sulfide (VMS) deposits. We propose a model where such caldera structures are submarine, polygenic, mostly silicic and associated with both long-lived crustal magmatic chambers and hydrothermal activity. Indeed one dominant process now proposed for VMS deposits implied a convecting system where both seawater and magmatic fluids are involved [e.g., *Large*, 1992]. Our data provide a volcanological framework, which explains the formation of large massive sulfide deposits. In this context, the observed spatial connection between silicic massive lavas and VMS at the regional scale might in fact reflect the spatial connection between calderas and VMS, through the spatial connection between caldera and lava domes.

[33] Moreover, such volcanological features point to a geodynamic environment consistent with subduction-related system such as arc or nascent back arc, as proposed for Kuroko-type deposits developed at the rear part of the arc [e.g., *Ohmoto and Skinner*, 1983] and in a global attempt, expended to all volcanogenic massive sulfide deposits [*Sawkins*, 1990].

5. Discussion: Geodynamic Evolution of the South Portuguese Zone

[34] Several models have been proposed in the last decades to define the geodynamic setting of the Iberian Pyrite Belt. In the early 80s back-arc spreading over the South Portuguese Zone continental crust, implying south-

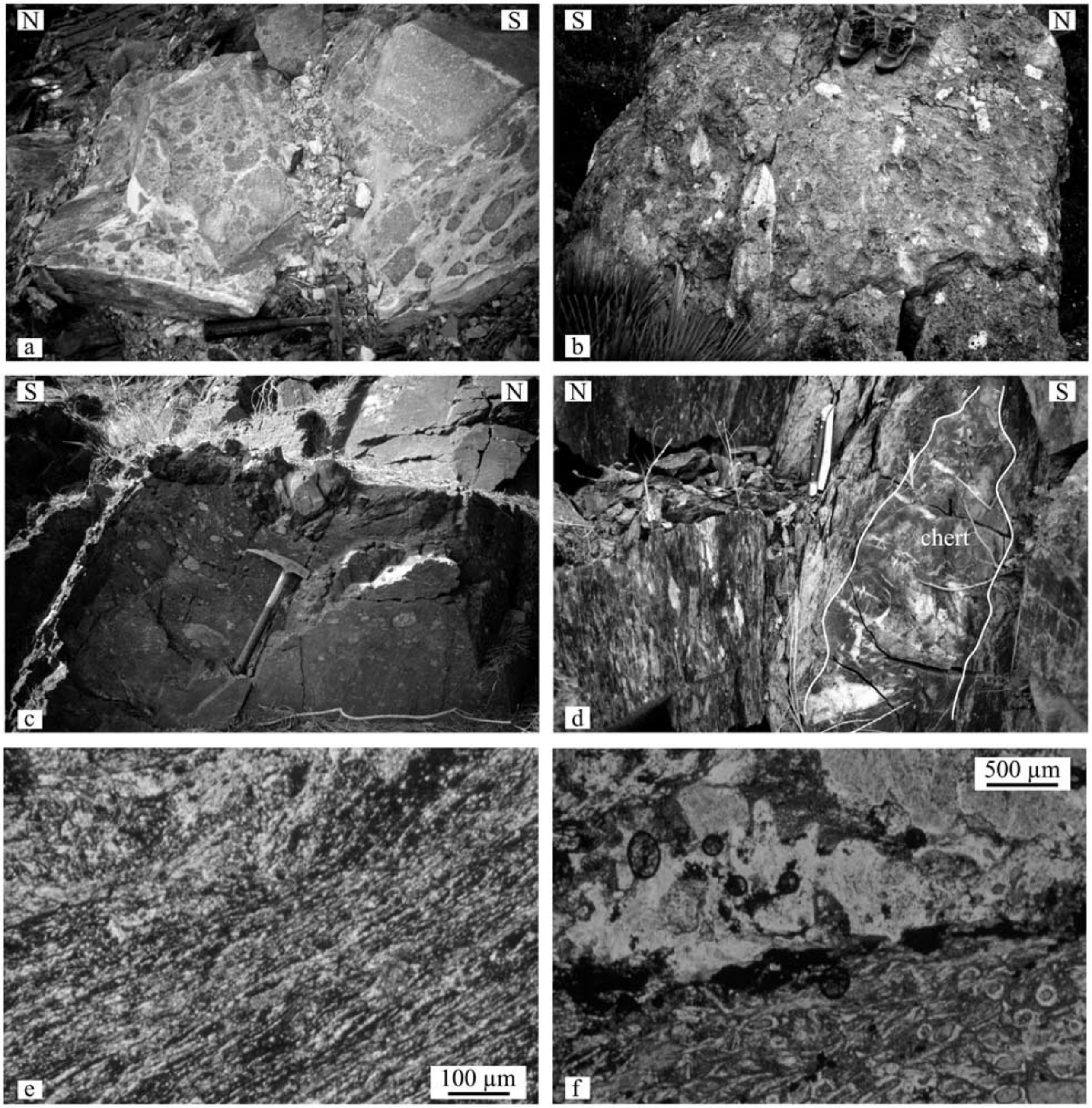

Figure 7. Volcanic and volcaniclastic facies in the Volcano-Sedimentary Complex. (a) Acidic lava showing peperitic features and granulation texture; (b and c) ignimbritic pumice-rich facies in the La Zarza area; (d) deformed ignimbrite (the so-called abigarradas facies) with chert block (El Perrunal-La Zarza); (e) Photomicrograph of thin section of an ignimbrite facies (SP187, El Villar). Original texture has been largely overprinted by diagenetic compaction, strong deformation and pervasive phyllosilicate alteration. The photograph shows volcaniclastic texture with part of a sericite-altered, tube-vesicle pumice clast in clastic, nonwelded, quartz-feldspar dominated matrix domain. (f) Photomicrograph of thin section of ignimbrite facies (SP8, Rio Odiel near Sotiel). Volcaniclastic texture with part of a pumice fragment in nonwelded volcaniclastic matrix. Mostly round vesicles in the pumice clast have been filled by chlorite while the vesicle walls have been replaced mainly by sericite.

ward subduction of the Ossa Morena Zone, was a popular model [*Munha*, 1983; *Soler*, 1973, 1980]. Other models included an island arc generated over a subduction zone [*Schütz et al.*, 1987], forearc basin [*Monteiro and Carvalho*, 1987], or paleoaccretionary prism [*Thiéblemont et al.*, 1994] have also been proposed. Last, the most currently proposed model describes pull-apart basins infilled with volcanogenic materials, developed coeval the north directed oblique

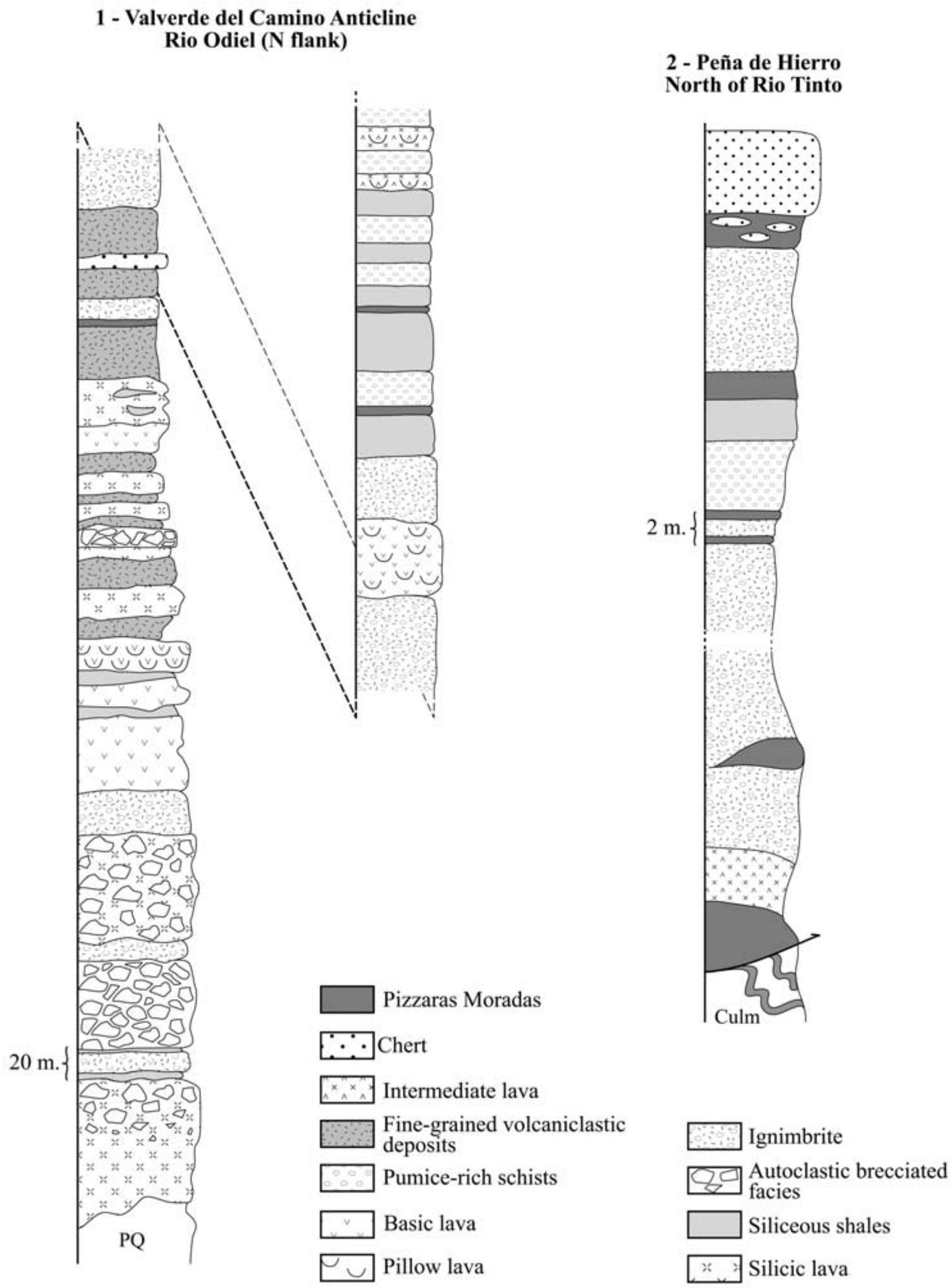

Figure 8. Stratigraphic columns in the Volcano-Sedimentary Complex (see Figure 2 for location).

subduction/collision of the South Portuguese Zone, [*Quesada et al.*, 1994; *Giese et al.*, 1994a; *Silva et al.*, 1990; *Mitjavila et al.*, 1997].

[35] This north directed subduction of the SPZ under the OMZ parautochthon, widely admitted nowadays, precludes some of the fore-mentioned models and is in agreement with the age and distribution of units composing the SPZ. Thus formations are getting younger toward the south from the Early/Middle Devonian Pulo do Lobo Antiform, the late Devonian-Visean Iberian Pyrite Belt, and the early Wesphalian Brejeira flysch formation in the southwestern Portugal (Figure 2). A logical distribution of the main domains from north to south is also recognized, from the oceanic domain to the north (the well-constrained Beja-Acebuches Ophiolitic Complex) and the related Pulo do Lobo Antiform accretionary prism, to the foreland basin (i.e., the south propagating Baixo Alentejo Flysch Group). In such a framework the position of the intermediate Iberian Pyrite Belt remains to be well constrained.

[36] On the basis of new structural data [*Onézime et al.*, 2002] and the facies analysis presented herein, we propose a five step geodynamic model for the South Portuguese Zone

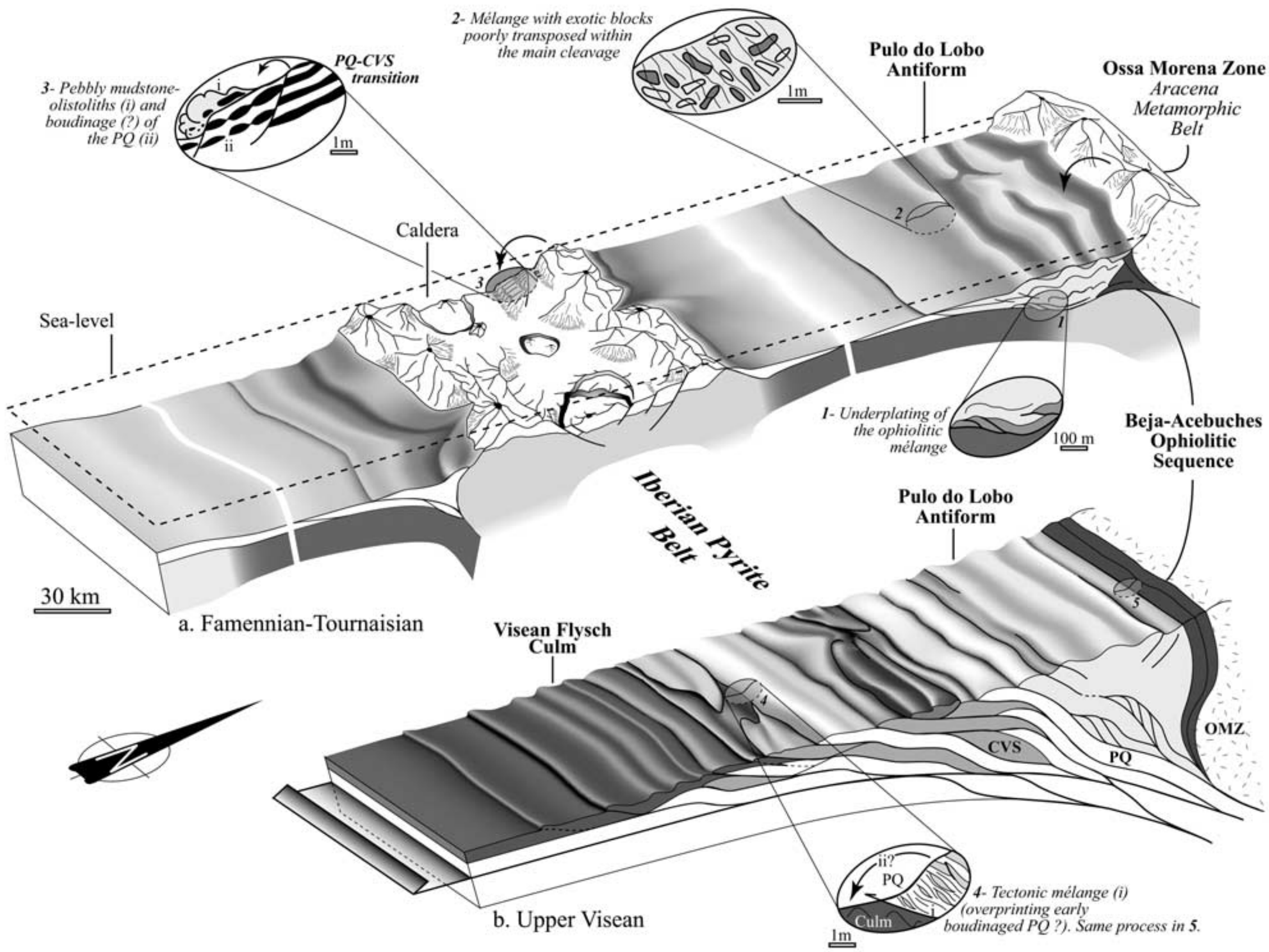

Figure 9. (a) Paleogeographic context associated with the Volcano-Sedimentary Complex and early mélanges setting at the Devonian-Carboniferous transition. (b) Upper Visean evolution of the South Portuguese Zone and structural environment of tectonic mélanges setting.

which attempts to explain the formation of the Iberian Pyrite Belt and particularly the Volcano-Sedimentary Complex and associated volcanogenic massive sulfide mineralizations (Figure 10).

5.1. Silurian-Middle Devonian

[37] The initial setting for the Silurian or Early Devonian includes three oceanic domains and two continental blocks, lying in between both Iberian parautochthon (Ossa Morena Zone) and the South Portuguese Zone (Figure 10a). These two isolated continental crusts are implicitly required to build our model. The northern block is associated with the setting of the Beja-Acebuches Ophiolitic Complex during the first north directed subduction, the oceanic crust needs a light crust (now cryptic) to be obducted on toward the south (Figure 10b). This first early to middle Devonian episode is recorded within the Acebuches Amphibolite and is evident in the early top-to-the-south kinematics observed within the preserved amphibolite facies (D_{1AA}, Figure 3). The obduction was followed by the deposition of the accretionary prism unit (Pulo do Lobo Formation), including early sedimentary mélange (e.g., Asserador mélange). The Peramora ophiolitic mélange, previously generated within the subducted oceanic domain, is also incorporated to the accretionary complex, but according to its paragenesis (presence of garnet with intermediate composition between Grossular/Spessartite/Almandine poles), buried along the Benioff plane and simultaneously deformed (D_{PPL}).

[38] At the same time, to the south of the oceanic complex (suture zone and accretionary prism), passive margin deposition takes place on the second intermediate block of continental crust and the SPZ block (Figure 10b). These continental detrital units are related to the basement of the Iberian Pyrite Belt and might correspond to the early sequence of the Phylites and Quartzites Group.

5.2. Upper Devonian-Famennian

[39] During the Upper Devonian a second convergent zone develops along the southern margin of the intermediate block, the Iberian Pyrite Belt block (Figure 10c). This

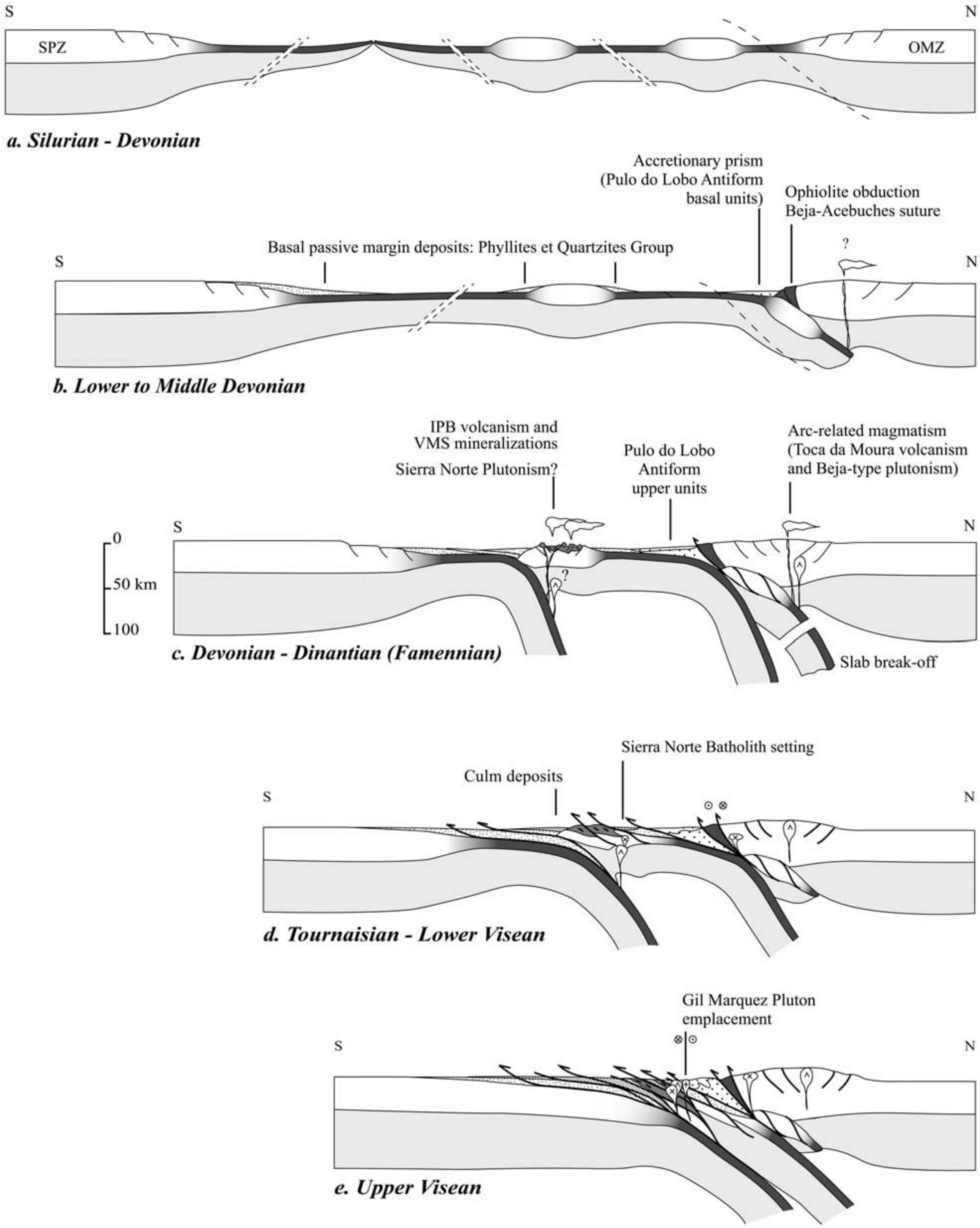

Figure 10. Geodynamic evolution of the South Portuguese Zone.

passive margin/active margin transition is recorded during the Famennian, by high-energy deposits setting (mélanges and olistoliths) toward the top of the Phyllites and Quartzites Group. This evolution is also associated with the development of the IPB magmatism in a continental arc environment (compare Volcano-Sedimentary Complex); the transtensional tectonics proposed by *Quesada* [1998] is not precluded here. The magmatism of the IPB and especially its affinity remains still controversial. It has always been described as bimodal based on Si contents [from *Lécolle*, 1977; *Munha*, 1983; *Routhier et al.*, 1980; *Mitjavila et al.*, 1997], but fieldwork and analyses (see same authors) show that many volcanic rocks plot in the intermediate andesitic domain. Moreover the explosive volcanism observed is much more abundant than what intrusive models typically propose [*Boulter*, 1993a, 1996; *Soriano and Marti*, 1999]. The great amounts of ignimbritic facies associated to felsic domes documented herein (especially in mineralized area such as La Zarza and Rio Tinto), strongly support the setting of both volcanism and massive sulfides in caldera environments. The heterogeneity of the magmatism, with a calc-alkaline geochemical affinity of acid rocks, tholeiitic and alkaline affinities for basic rocks (basalts), although partly "incompatible," refers to a context commonly observed within arcs. The dip of this second subduction zone is also toward the north. We favor this model to another (for instance, a south directed subduction developed along the northern edge of the block) because the proposed Iberian Pyrite Belt arc appears to be rooted northward in the Sierra Norte Batholith.

[40] We admit that the arc interpretation might appear controversial, especially considering some conclusions obtained by several petrological studies suggesting that a forearc or back-arc environment would be more suitable regarding basic rocks signatures [e.g., *Munha*, 1983; *Thiéblemont et al.*, 1998]. However, geochemical data are variously assessed and, on the contrary, others [*Mitjavila et al.*, 1997] consider that basaltic rocks do not show any subduction-related affinity and favor a setting in intracontinental pull-apart basins developed due to coeval transtensive tectonics related to oblique collision of the SPZ to the Iberian parautochthone (OMZ). These contradictions and the successive tectonic models proposed underline the extreme difficulty to interpret a geodynamic setting for the IPB based on petrologic data. Indeed the heterogeneity of the geochemical signatures remains a main problem; *Thiéblemont et al.* [1994] emphasized this problem and showed that even if basic rocks can be considered as tholeiites, their trace elements analyses discriminate continental tholeiite, back-arc tholeiite, arc tholeiite, and also E-MORB. As we mentioned above, we believe that the intermediate facies were underestimated and then we do think that an arc series might be represented in the IPB. However, an "in-between" hypothesis being able, to a certain extent, to reconcile different (not all) points of view might be envisaged. We can indeed suggest a setting of part of IPB volcanism and related mineralizations at the rear part of the (continent-based?) arc or even in a nascent back-arc environment like Kuroko type deposits and as it has been proposed for the Mount Windsor VMS mineralizations [*Stolz*, 1995]. This incipient back arc was linked with a rifting affecting the arc area, which fits with the extensional tectonics already described, and strengthens the similarities with the Kuroko-type deposits environment and genesis during the Miocene, at the initiation stage of the Sea of Japan opening.

[41] To the north of the Iberian Pyrite block, the coeval north directed subduction is responsible for calc-alkaline magmatism in the Ossa Morena Zone. This is related to the Toca da Moura volcanism (Santa Susana region, Portugal [*Santos et al.*, 1990, 1987]) and the gabbroic/tonalitic intrusions such as the Beja gabbro [e.g., *Andrade*, 1983]. The late Devonian emplacement is supported by the circa 350 Ma U-Pb zircon date from Beja Massif samples [*Pin et al.*, 1999]. On the Spanish side of the suture, andesite magmas with boninite affinity have been described and suggest a strong thermal anomaly that can be variously assessed: a slab window resulting from ridge subduction [*Castro et al.*, 1996a] or a slab break off as proposed here (Figure 10c). In such an environment the lack of subduction-related volcanism in the southern OMZ remains a problem. However, at the same time the accretionary prism develops (Pulo do Lobo and Ribeira de Limas Formations), and the large amounts of volcanic fragments, acidic and mafic, suggest an important arc dismantlement [*Giese et al.*, 1994a].

[42] During the Upper Devonian, progressive transition from top-to-the-south kinematics to sinistral strike-slip tectonics develops within the Beja-Acebuches Ophiolitic Complex (i.e., beginning of the D_{2AA} episode). In the same way, this period must correspond to the very first steps of the main deformation phase observed within the Pulo do Lobo Antiform (D_{1PL}).

5.3. Visean

[43] During the Lower Carboniferous, both of these episodes reach their paroxysmal features (Figure 10d). Within the Beja-Acebuches Ophiolitic Complex, this is supported by the formation of a mylonitic foliation and a subhorizontal stretching lineation associated with sinistral shearing and a coeval retrogressive greenschist facies metamorphic phase. This episode seals the transition from early north directed subduction to oblique collision [e.g., *Castro et al.*, 1996a; *Quesada et al.*, 1994]. In our opinion, the circa 340–330 Ma $^{40}Ar/^{39}Ar$ ages on amphibole are more likely the time of this transition rather than any cooling event as suggested by *Dallmeyer et al.* [1993] and *Castro et al.* [1999], the $^{40}Ar/^{39}Ar$ system being reinitialized during the D_{2AA} phase of deformation.

[44] Within the Pulo do Lobo Antiform, the turbiditic Santa Iria Formation has been deposited and likewise the whole PLA has acquired the fan-like geometry, with localized refolding (D_{2PL}). However, the oblique collision implies a dissymmetry of the structures. While the early features are preserved in the western central part of the accretionary prism (folded S_0, opposite kinematic criteria), its eastern ending is more intensively deformed, S_0 is no more or barely observed. This observation strengthens the

oblique collision model. In the Iberian Pyrite Belt, this is the beginning of the south directed thin-skinned tectonics (D_1) coeval the synorogenic Culm deposits setting. During the upper Visean the collision reached its climax, as recorded in the Iberian Pyrite Belt by the D_2- and D_3-related structures (Figures 5 and 10e). On a metallogenic point of view, this period is correlated to the development of the syntectonic to late tectonic stockwork.

[45] If we envisage the rear arc or nascent back-arc position for the VMS mineralizations and associated magmatism, we have to consider that during the Visean, at least part of the frontal arc developed to the south has been either recycled in the Culm (see the large conglomeratic lenses described in the flysch unit, section 2.3.) and/or partly overthrust by northward rooted units due to the south directed thin-skinned tectonics.

[46] Along the IPB-PLA boundary, the last step of our model is associated with the emplacement of syntectonic plutons such as the Gil Marquez granodiorite during a late right-lateral wrenching event, mostly recorded in the southern edge of the PLA (Figure 10e). The Sierra Norte batholith emplacement eventually occurred (or ceased) during this late episode of deformation.

6. Conclusion

[47] The South Portuguese Zone, southernmost unit of the Iberian Massif represents a segment of the Variscan Belt of western Europe which remains hard to correlate with other known domains of the Belt. Indeed the relationship of the Beja-Acebuches Ophiolitic Complex with Variscan sutures remains hypothetic. Moreover, this ophiolitic sequence is sometimes interpreted as belonging to a former small oceanic basin (back-arc or trantensional basin). We believe that this ophiolitic complex represents a main suture zone within the Variscides, obducted toward the south during the north directed subduction of the oceanic crust. This idea complies with the presence, to the south, of the Pulo do Lobo Antiform, interpreted as an accretionary prism on the bases of the tectonic (fan-like distribution of the structures) and lithologic (sedimentary and tectonic mélanges) patterns.

[48] The enigmatic Iberian Pyrite Belt developed southward the oceanic/accretionary complex in the central part of the South Portuguese Zone. Volcanic facies analysis reveals important amount of felsic pyroclastic deposit (ignimbrite) associated with felsic lavas (flow and dome facies) both submarine. The combination of these elements suggests the presence of important polygenic(?) caldera structures within the Iberian Pyrite Belt. On a tectonic point of view such volcanologic environment suggests a setting in a continental arc environment, implying the transition from a passive to an active continental margin developed above a second north directed subduction zone. This evolution is in part supported by mélange formations developed at the PQ-VSC transition.

[49] In some cases the geographic relationships between lava dome, ignimbrite and volcanogenic massive sulphides deposits can be observed (e.g., La Zarza), suggesting that a caldera environment is closely related to the genesis and the deposition of major ore bodies. Thus this model provides a volcanological framework likely to explain the formation of large VMS ore bodies. However, this model cannot be extended to all deposits recognized around the belt, some of them being hosted by highly deformed siliceous/carbonaceous shales and underlined by a feeder stockwork (compare Iberian-type mineralizations [*Saez et al.*, 1999; also *Leistel et al.*, 1998; *Routhier et al.*, 1980]).

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